Deflection Predictions of Involute-shaped Fuel Plates using a Fully-Coupled Numerical Approach

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Abstract

This paper describes the modeling and simulation of fluid structure interactions (FSI) of involute-shaped fuel plates used in nuclear research reactors. We believe this to be the first time that this type of application is described in the literature using a fully-coupled, and monolithic, finite element approach. The simulations are validated against plate deflection data for the conceptual design of the Advanced Neutron Source Reactor (ANSR), which was envisioned to be the world's most powerful nuclear research reactor for neutron scattering and other applications, but was ultimately never completed. The high performance of the ANSR creates a bounding envelope for

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involute-shaped research reactors such as that used in the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL) which is undergoing research for the conversion from highly-enriched uranium (HEU) to low-enriched uranium (LEU) fuel. As such, the findings from the present FSI analyses carried out herein for the ANSR plates provide good guidelines and inform designers what should be expected for the next generation of plates in the HFIR. It is shown herein that the current approach can accurately capture the leading-edge deflections of the involute-shaped plates and simulations can predict the 'S-shaped' deflection of the first mode instilling confidence in the methodology.
Keywords: Fluid-Structure Interaction, Thermal-hydraulics, High Flux Isotope Reactor, Involute Fuel Plates

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1. Introduction

The High Flux Isotope Reactor (HFIR), located at the Oak Ridge National Laboratory (ORNL), has been providing the highest neutron flux in the United States since 1965. Conceptual designs of the reactor began in 1958 utilizing highly-enriched uranium (HEU) to run at 100 MW_{therm}. The reactor ran at this power until 1986 when embrittlement of the reactor vessel became a concern and the power was reduced to 85 MW_{therm} where it continues to run today [1].

A call has been issued by the U.S. Department of Energy's (DOE) National Nuclear Security Administration (NNSA) that states that all research reactors in the United States should convert their HEU fuel to low-enriched uranium (LEU) fuel as part of the Global Threat Reduction Initiative (GTRI)

[2]. As part of the call, the research reactors are to be converted to use the LEU fuel without significant changes to the design of the reactors while ensuring a high level of safety without compromising the scientific capabilities of the reactors.

HFIR is one of the remaining five high performance research reactors to be converted in the United States. Because the internal fuel meat of the fuel plate is being redesigned for the LEU fuel, the safety basis for the operating reactor must be updated, and extensive thermal-hydraulics analyses must be performed with the redesigned fuel. For each cycle of the reactor, the current safety assessment is performed using various calculations and codes. The two main codes used for the thermal hydraulic calculations of the HFIR are the Steady State Heat Transfer Code (SSHTC) [3] and a modified version of RELAP5 [4], both of which are based on one-dimensional flow physics. For detailed information about the implementations of these codes, the readers are referred to the Safety Analysis Report (SAR) [5]. To improve our understanding of the multiphysical phenomena in the reactor, state-of-the-art high-fidelity codes must be utilized. For this purpose, COMSOL Multiphysics [6] code is chosen. In particular, COMSOL has been used for investigating the thermal-hydraulics [7, 8, 9, 10, 11, 12, 13, 14, 15, 16], thermal-structure interaction [17] and reactor kinetics [18**?**] of the HFIR core.

The current design of the HFIR core consists of 540 involute shaped fuel plates placed in two concentric elements with 171 plates in the inner element and 369 plates in the element. The plates are 50 mils thick and they are separated by a spacing of the same distance as depicted in Figure 1. The primary goal of this work is to determine the deflection of the aluminum plates due to cooling water flow in order to predict changes in the flow channel geometry between the plates.

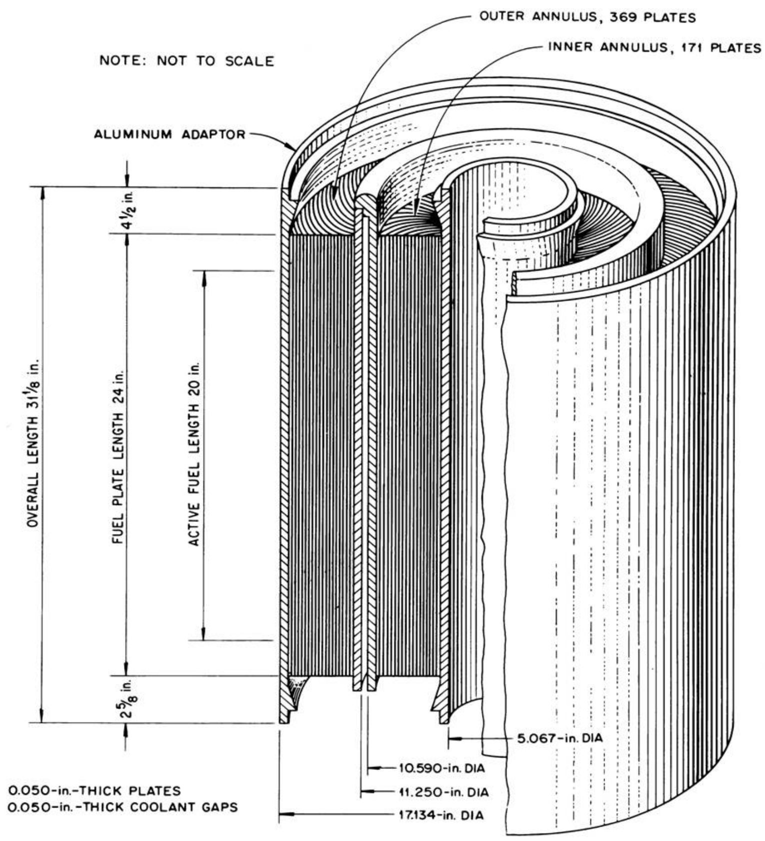

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Figure 1: Cutaway of the HFIR core.

Plate deflection has been an area of interest beginning with preliminary investigations of high-flux plate reactors at ORNL in 1948 [19]. During their experiments, Stromquist and Sisman observed vibrations for plates with thicknesses similar to the current HFIR design. Miller later developed an estimate of the maximum flow speed that a series of parallel plates could sustain before collapse, aptly named the Miller Critical Velocity, M_c [20]. For a flat plate with fixed edges, the Miller Critical Velocity is defined as

$$M_c = \left[\frac{15Ea^3h}{\rho b^4\left(1-\nu^2\right)}\right]^{1/2} \tag{1}$$

where E is the Young's Modulus of the plate, a is the plate thickness, h is the flow channel thickness, ρ is the density of the coolant fluid, b is the width or span of the plate, and ν is the Poisson's ratio of the plate. Equation (1) is based on the assumption of incompressible, potential flow and an elastic wide-beam theory. Miller also assumed identical mass flow rates between all channels. The resulting equation roughly predicts the velocity for which the pressure difference between the plates is sufficient to result in a finite level of deflection. Because of its simplicity, the Miller Critical Velocity has become a standard for plate deflection analyses.

The Miller Critical Velocity has been (and continues to be) the topic of many experiments to understand the applicability of the theory. Most researchers [21, 22, 23, 24] found that the M_c was based on conservative assumptions. Groninger and Kane [21] and Smissaert [22] found that the plates began to vibrate around twice the value of M_c. An exception to this finding was reported by Ho et al. [25] for which plate buckling was observed at a speed below M_c suggesting the Ho study to be outside the norm.

As it became clear that the Miller Critical Velocity was conservative, many researchers began to search for improvements to the model. As such, investigators started accounting for more advanced physical models. For example, Johansson [26] incorporated viscous and flow redistribution effects. Kane [27] developed a model that incorporated manufacturing deviations to the flow channels and found that large channel deviations resulted in greater plate deflections. Scavuzzo [28] modeled entrance and exit effects and Wambsganss Jr. [29] pointed out the need for the inclusion of second-order effects to the original version of Miller's equation.

Researchers then began to include other analytical techniques in order to provide a better estimate of the plate deflections of parallel fuel plates. Wick [30] explored a wave propagation technique, and also investigated an eigenfrequency approach with end plate effects [31]. Kim and Scarton [32] used Schlichting's boundary layer theory while Kerboua et al. [33] incorporated potential flow theory around a single plate to analyze a series of plates. Cekirge and Ural [34] and Pavone and Scarton [35] both focused on improving the plate theory to enhance the model.

It became evident that one-dimensional flow simplification used in previous studies was insufficient and researchers began to use two- and three-dimensional models for the fluid flow. Guo and Païdoussis [36] utilized a Galerkin method to model a two-dimensional plate with a three-dimensional flow field. Several researchers sought to determine the natural frequencies of the plates including Kim and Scarton [32], who combined turbulent effects with a frequency analysis of thin plates. In a different study, Cui et al. [37] used a whetting method to determine the frequencies, and Michelin and Llewellyn Smith [38] analyzed flutter by examining n-series of plates.

Although these techniques provided good insight into the deflection of parallel plates, there is still much to be studied about fluid-structure interactions in such systems. As high performance computing (HPC) resources become more available, the use of computational models to simulate fluid-structure interaction (FSI) between the plates and the coolant flow is becoming more feasible. Recently, Roth [39] was able to use computational fluid dynamics (CFD) to simulate the flow between fuel plates but was unable to observe plate deflections. Kennedy [40] used two segregated codes, one for modeling the fluid flow and another for modeling the structural response. This approach resulted in a loosely-coupled approach, which proved to have significant stability problems. To address the potential numerical stability issues, the work presented herein utilizes a fully-coupled (monolithic) approach which incorporates the flow physics and structural mechanics in a unified solver [41]. In previous work [42], this approach has been shown to produce reasonably accurate computations and results have been validated against the experimental data of Smissaert [43].

This work builds upon the previous reported analyses and is particularly focused on accurate modeling of involute plate configurations that are representative of the HFIR. In the late 1980s and early 1990s, a new reactor, called the Advanced Neutron Source Reactor (ANSR), was proposed at the ORNL to provide another high-flux source of neutrons. During the development of this reactor design, numerous experiments were performed, including deflection experiments of the involute-shaped fuel plates. These experiments provide the only available plate deflection data to date for involute-curved plates. As such, the ANSR experiments were chosen to validate the adopted monolithic methodology for accurate prediction of deflections for a proposed updated design of the HFIR LEU-fueled plates.

2. ANSR Experiment

As discussed earlier, the Advanced Neutron Source Reactor was proposed as an alternative high-performance, heavy-water research reactor at ORNL. The reactor design incorporated involute fuel plates – similar to those used in the HFIR – with cooling flow rates at approximately 25 m/s. The design met or exceeded the neutron flux characteristics of the HFIR yielding what would have been the highest neutron flux reactor in the world. Due to the challenges associated with extremely high flow rates, extensive analyses were performed to ensure the stability and integrity of the fuel plate structure in the reactor [44, 45, 46, 23, 47, 48, 49, 50].

The ANSR HEU cores were designed to have two fuel elements similar to the HFIR except that the cores in the ANSR were to be stacked one after the other instead of the concentric configuration used in the HFIR. A later LEU core consisted of three fuel elements. The conceptual HEU core design is provided in Figure 2 for interested readers.

The flow through the ANSR HEU core (hereafter referred to as the core) is from the bottom to top of Figure 2, and the nomenclature of upper element and lower element is used to describe the larger and smaller cores, respectively. The upper element consists of 432 plates with an inner diameter of 175 mm and an outer diameter of 235 mm; the lower element consists of 252 plates with an inner diameter of 102 mm and an outer diameter of 168 mm. Each fuel element is 527 mm long with 507 mm being fueled.

During the design process for the ANSR, many experiments were performed in order to help establish the safety basis for the reactor operations and to better quantify the design requirements. Flow tests measuring ther-

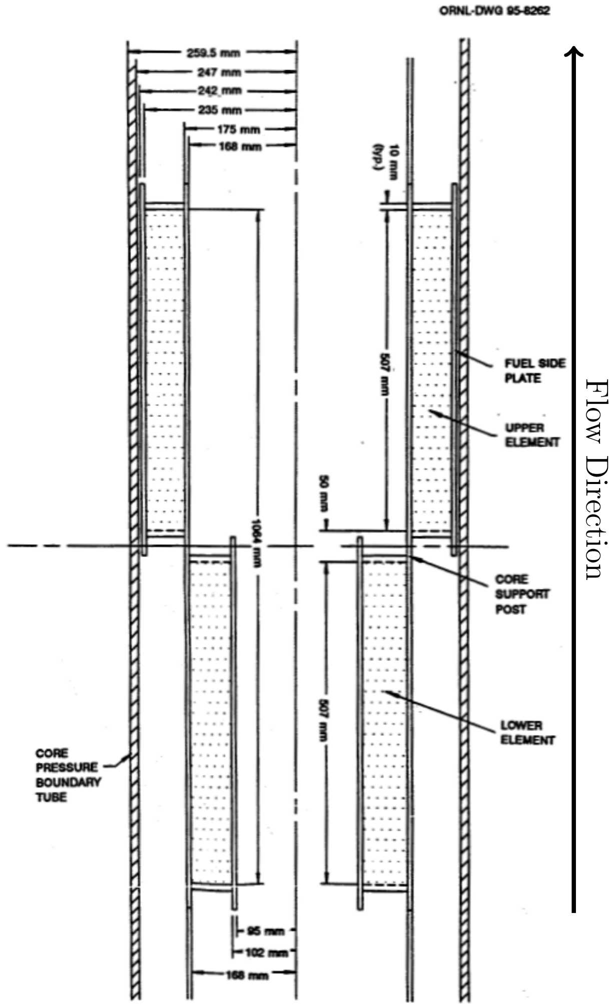

Figure 2: Proposed configuration of the ANSR HEU core [49].

mal characteristics of the fuel plates were performed that were designed to measure the heat transfer capabilities of the design [51, 52, 53, 54]. Another set of experiments were performed to test fuel-plate deflections due to the coolant flow [44, 45, 46, 23, 47, 48, 49, 50].

The emphasis of this paper will be on the experiments performed to establish the deflection characteristics of the plates. The experimental setup consisted of five “fuel” plates made out of PVC plastic. The experiment was performed on this “model” of involute-shaped plates of the upper element and six full flow channels around the five plates. A dimensional analysis was performed by the researchers to predict the leading edge deflection for a series of aluminum plates. The analysis, which is described by Swinson et al. [45], assumes that the Poisson's ratio of each material is approximately the same and thus the measured deflection of the PVC plate equals the deflection of the aluminum plate (referred to as the prototype). With this assumption the inlet velocities (and the flow rates) for the prototype and the model are related through

$$\delta_p(\text{prototype deflection}) = \delta_m(\text{model deflection}) \tag{2}$$

$$V_p = V_m\sqrt{E_p/E_m} \tag{3}$$

where δ is the deflection of the plate, V is the inlet velocity and E is the Poisson's ratio of the plates. Using Eq. (3), Table 1 presents the inlet velocities for both the prototype and models along with the Re of each inlet velocity. The Reynolds number in Table 1 is calculated using the assumption that the hydraulic diameter, d_h, can be set to twice the channel thickness for a channel whose width is much greater than its thickness. For the upper element, the channel width, also the arclength of the involute curve, is approximately 71.2 mm long while the channel thickness is 1.27 mm; thus, Re is determined from twice the channel thickness of 1.27 mm.

The deflection of the plates was measured using strain gauges at five evenly spaced locations along the length of the plates. The deflection was

Table 1: Inlet velocities for the ANS prototype and model simulations and experiments.

V_m, m/s	Re_m	V_p, m/s	Re_p
3.58	9093	17.35	44,069
5.18	13,157	25.09	63,729
6.65	16,891	32.24	81,890
8.32	21,133	40.32	102,413
10.03	25,476	48.63	123,520

measured at the leading and trailing edges as well as at 1/4, 1/2, and 3/4 locations along the plate. The experimenters used an inlet plenum of 527 mm and this length was used in the simulations. The outlet section length was not specified in the papers reviewed for this work. Table 2 provides the physical properties for both the PVC and aluminum plates used for the analysis. The

Table 2: Plate physical properties used for the ANSR experiments.

Material	E, GPa	ρ, kg/m^3	ν
PVC	2.937	1350	0.35
6061 Aluminum	69	2700	0.33

density of the PVC plate was not specified so an average of the density range found in Titow [55] was used for the simulations.

The experimenters performed a series of deflection measurements using the ANSR plates and provided the deflections along the plates for various flow speeds. In addition, using the same setup they installed a PVC plate with the shape of a fuel plates from the HFIR inner fuel element (IFE) and reported the deflection measurements at the leading edge.

3. Computational Model

As mentioned earlier, the ANSR experiment utilized PVC plates with Eqs. (2) and (3) used to predict the coolant speeds for the equivalent aluminum plate deflections. For the computational model, the properties of the aluminum plate and PVC plate were used to compare to the deflections from the experiments. The FSI computations were performed using the commercial software COMSOL [6], which uses a finite element method (FEM) for the discretization of the governing equations that model fluid and structural dynamics.

The working fluid is water modeled by the incompressible Reynolds-Averaged Navier-Stokes equations given as

$$\nabla \cdot \mathbf{u}_f = 0 \tag{4}$$

$$\rho_f \frac{D\mathbf{u}_f}{Dt} = \rho_f \mathbf{g} - \nabla p + \mu \nabla^2 \mathbf{u}_f \tag{5}$$

where $\mathbf{u}_f$ is the velocity of the fluid, ρ_f is the density of the fluid, $\mathbf{g}$ is gravitational acceleration, p is the pressure, and μ is the dynamic viscosity of the fluid.

Depending on the plate-type being analyzed (aluminum or PVC), the inlet velocity was set accordingly. Table 1 indicates that for all inlet velocities considered, the flow is turbulent according to the Reynolds number. In this work, the turbulent viscosity is modeled using a modified k-ϵ turbulence model with wall-functions [56], and the constants used for the turbulence model are provided in Table 3.

Table 3: Constants used for the k-ϵ turbulence model for this study.

Constant	Value
C_μ	0.09
$C_{\epsilon 1}$	1.44
$C_{\epsilon 2}$	1.92
σ_k	1.0
σ_ϵ	1.3

The structural dynamics of the PVC plates is modeled using the following linear elastic model:

$$\rho_s \frac{\partial^2 \mathbf{u}_s}{\partial t^2} = \nabla \cdot \sigma + \mathbf{F}_s \tag{6}$$

where ρ_s is the density of the plate, $\mathbf{u}_s$ is the displacement of the plate, σ is the strain and $\mathbf{F}_s$ are the external body forces on the plate. At the fluid-structure interface, the surface displacement and velocity of the plates are imposed as boundary conditions in the fluid dynamics solver, whereas the forces due to pressure and shear in the fluid are imposed as external forces in the structural dynamics solver.

The coupling of the fluid and structural mechanics is handled using a monolithic approach in which the entire domain, including boundary conditions, is discretized and assembled into a single matrix. The problem is then solved using a fully-implicit Newton's method. This approach has proven to be very stable compared to a loosely coupled segregated approach [57], and it was shown that the monolithic approach provides accurate and stable results for a series of flat plates that undergo large deflections [42].

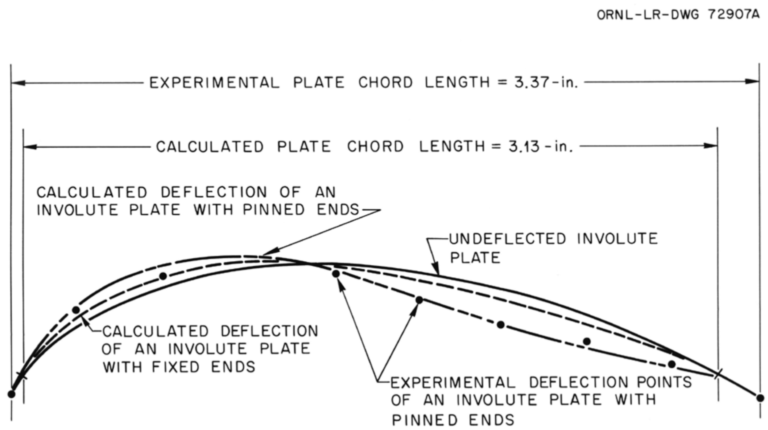

Figure 3: The leading edge deflection of the HFIR plates predicted by Luttrell which is currently used in Section 4.2 of the HFIR SAR.

4. Validation Study for the ANSR Experiment

Previous analyses of the ANSR and HFIR by Luttrell [49] predicted an "S-shaped" deflection at the leading edge as shown in Figure 3. This prediction is used in the HFIR SAR where an eigenfrequency analysis of the 1st mode of the plates confirms this "S-shape" assumption. The simulation of the plates, using the present FSI formulations, also results in similar type of deflections at the leading edge as presented in Figure 4.

Deflection calculations were performed for a single plate to compare the monolithic FEA FSI formulation to the experiments performed by Swinson et al. [45]. The properties for the aluminum plate and prototypical inlet velocities were used as simulation model inputs, and the maximum total deflection of the plates at the five locations is presented in Figure 5. Also shown in the same figure are the deflections observed during the experiments of the ANSR. It must be noted that the flow velocities for the ANSR are much

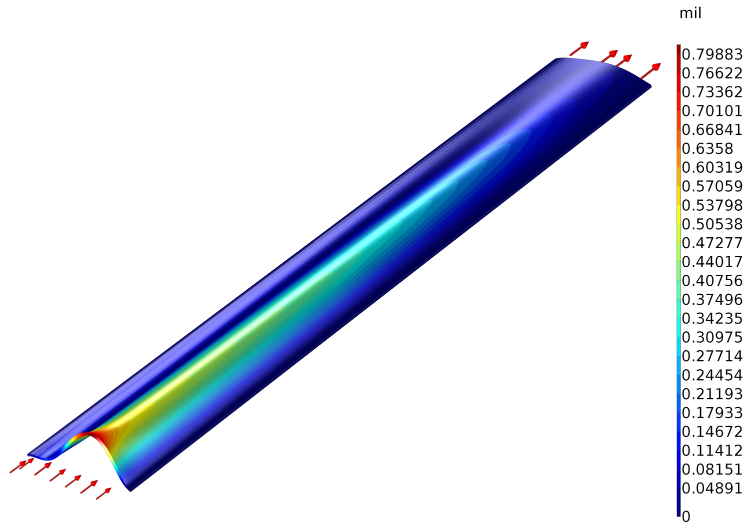

Figure 4: The total deflection of a single aluminum ANSR plate at 17 m/s showing the first mode deflection of the plate with a maximum deflection of 0.79 mils.

higher than that of the HFIR (15 m/s), and this pushes the code near the threshold of stability. The mesh consisted of a free mesh along the sidewalls of the plates with a swept mesh in the span-wise direction of the plate with a boundary layer mesh along the no-slip walls. The final mesh consisted of 270,264 elements and satisfied the y^+ values for the k-ϵ turbulence model.

As can be seen, the simulations accurately predict the experimental deflections well for the entire length of the plate. As with the previous flat plate comparison, the leading edge deflections match most accurately [42]. An important data point to observe is at the trailing edge deflection of the highest velocity of 40.32 m/s. At this condition, the experiments report deflections in the opposite direction and our simulations also capture this behavior.

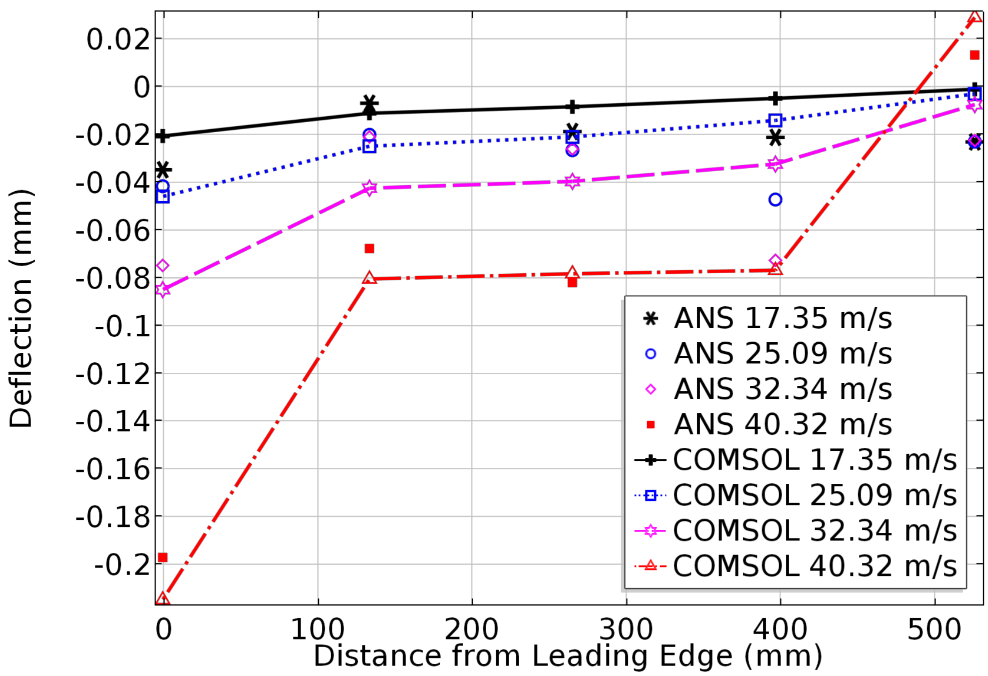

Figure 5: Comparison of the deflections of the Aluminum ANSR plate FSI simulations to the experiments.

5. HFIR Fuel Plate Deflection Predictions

The ANSR designers also measured deflections of a single HFIR IFE plate in their test rig. Because the main purpose of the experiment was to determine the deflections of the ANSR fuel plates, the HFIR plate experiment only measured the leading edge deflections of a single HFIR plate. Again, the plate was made using PVC and lower velocities were used to predict a prototype aluminum deflection. In this work, several simulations are performed to help guide the HFIR safety analyses for best practice using FSI. PVC plates were modeled for validation purposes. Using the ANSR simualtions (with their higher experimental deflection fideltity) and the HFIR simulations (with the leading edge experimental deflections) as validation for the techniques, the aluminum plates were modeled for current HFIR coolant speeds of approximately 15 m/s.

The simulations for the PVC plate together with measured deflections are provided in Figure 6. The leading edge deflections agree qualitatively with the experiments and are consistent with the simulations performed for the ANSR plates. It is clear that the predicted deflections are around 10-20% lower than those observed in the experiments. Also, since the full uncertainties in the experiment are not reported, the error bars are not provided in these graphs.

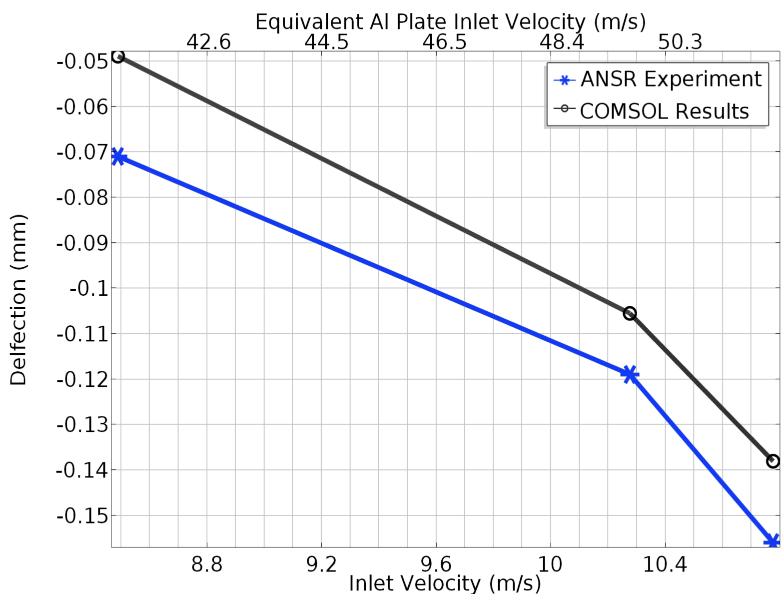

Figure 6: PVC plate deflections for the HFIR IFE compared to the experiment. The equivalent inlet speeds for an aluminum plate are provided at the top of the figure for comparison.

With established confidence in the involute-curve simulations compared to bounding experiments, a prediction of the HFIR plate at 15 m/s was performed next. Both solid aluminum plates and aluminum plates with the proposed LEU fuel design using Uranium-10Molybdenum (U10Mo) fuel were considered. The physical characteristics of the the U10Mo were taken from Burkes et al. [58]. Simulation results of the deflections along the full plate are provided in Figures 7 and 8 for the all-aluminum and U10Mo fuel, respectively. A comparison of the leading edge deflections of the two plates is provided in Figure 9.

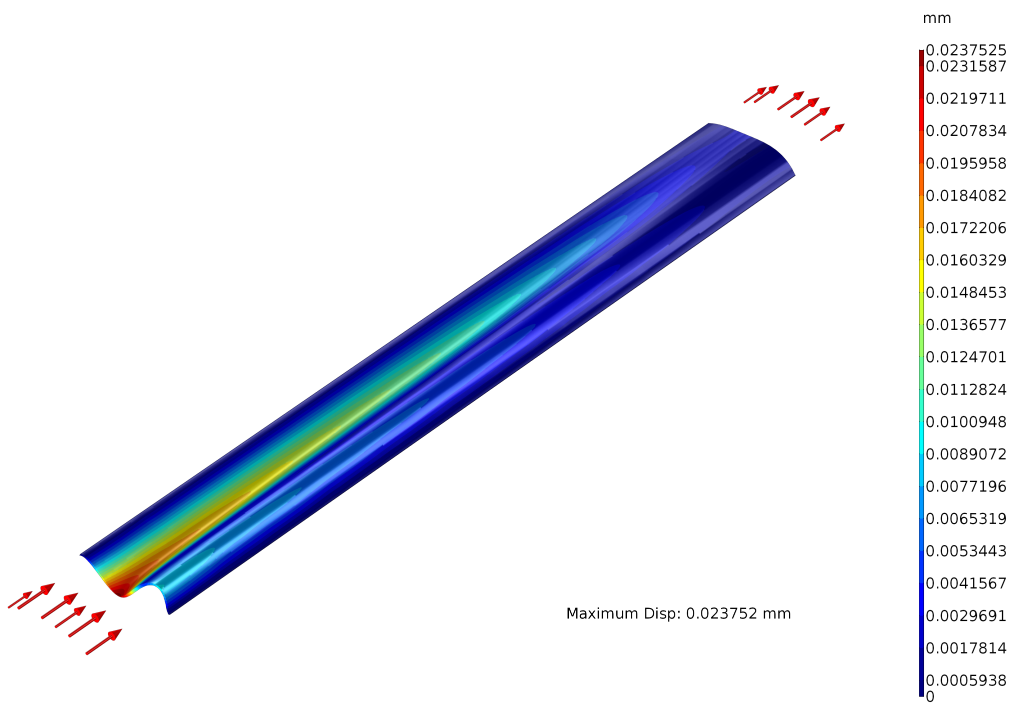

Figure 7: The total deflection of a solid aluminum HFIR IFE plate at 15 m/s showing the first mode deflection of the plate with a maximum deflection of 0.928 mils.

The simulations of the aluminum HFIR plate with a coolant velocity of

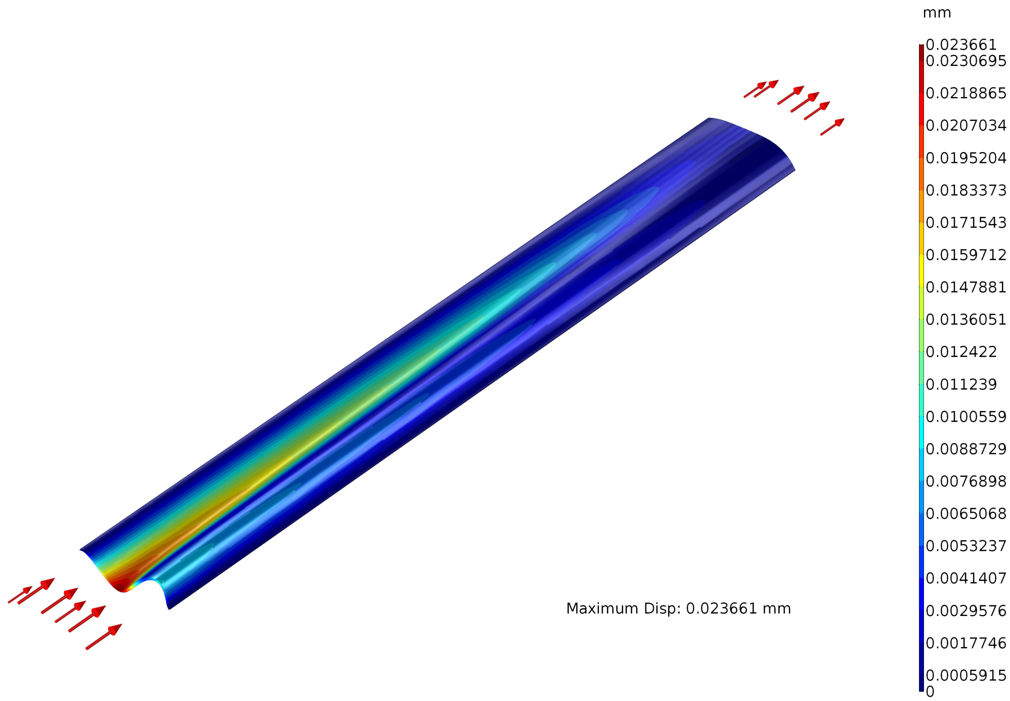

Figure 8: The total deflection of an aluminum HFIR IFE plate with the proposed LEU fuel profile at 15 m/s showing the first mode deflection of the plate with a maximum deflection of 0.932 mils.

15 m/s have provided information on the reduction in flow and the maximum displacement of the leading edge of the plates. When calculating the deflection of the plastic HFIR plate for validation with the experiment, mesh smoothing instabilities arose resulting in inverted meshes at the higher velocities. For the aluminum plates, this was not an issue and results were obtained for coolant velocities comparable to what is seen in the reactor. The small deflections predicted by the model (on the order of 1 mil) for the aluminum IFE plate are well within the specifications of the HFIR SAR.

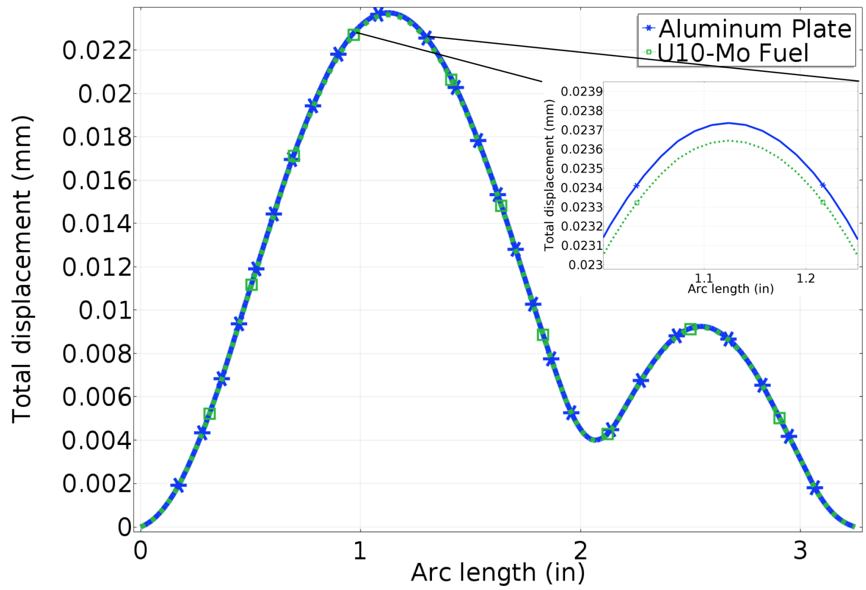

Figure 9: The leading edge deflection of a HFIR IFE plate at 15 m/s is compared for the solid aluminum plate and the plate with the proposed LEU fuel profile.

Looking at Figure 9 it is clear that the inclusion of the LEU fuel meat does not significantly alter the deflection compared to the solid aluminum plate. This is an important finding since the inclusion of the LEU fuel meat contour significantly increases the complexity of the mesh generation and ultimately the computational times. As such, future simulations considering only solid aluminum plates may simplify the simulation setup and process.

6. Conclusion

The transition from the simulation of flat fuel plates to involute-curved fuel plates is essentially straightforward. The techniques developed for the simulations of the previously-analyzed Smissaert [42] flat plate experiment worked well for the more complex geometry of the curved plates. As with the Smissaert experiments, the leading edge deflection is accurately predicted in the ANSR experiments and the trailing edge deflections are slightly less accurate.

Predicting the deflection of the HFIR fuel plate proved to work just as well as the ANSR simulations. Again, with good agreement with experiments, the prediction of the deflection of the HFIR plate with the LEU fuel inserted shows the difference in maximum deflection to be very small. The maximum deflections were below 1 mil for the coolant velocities seen in the HFIR. With such small differences between the solid aluminum and U10Mo plates, it would be reasonable to use the solid aluminum plate to predict the deflections and reduction on flow area to reduce the meshing complexity within the plates.

Work on the conversion of the HFIR to LEU fuel is still ongoing and there is more that can be done for the FSI of the fuel plates. In particular, the deflection calculations could be coupled with the conjugate heat transfer of the fuel heat generation to better quantify the deflection effects on the coolant of the reactor initially used with the SSHTC. Additionally, this could be coupled with a thermal-stress calculation to include movement of the plate due to the heat gradient along the fuel plates.

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